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A New Collider Upgrade Proposal; Increasing the Pbar-P Collider Energy

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Abstract

An upgrade to the pbar-p collider is proposed which involves replacing the present superconducting Tevatron magnets with higher field magnets. Dipole fields of 8.8 Tesla give 2 TeV on 2 TeV for an estimated cost of less than $200M. Luminosity projections are made with suggestions for additional improvements.

Introduction

The two upgrade proposals which are now being debated are based on the premise that a substantial luminosity increase will be essential to the Tevatron's utility, especially in the period between 1994 and the era of the SSC. Both the "20 GeV Rings" version of the pbar-p collider upgrade and the "New Main Injector" p-p collider use the existing MR tunnel to achieve 1 TeV collisions with luminosities between 5 10^{31} and 5 10^{32}.

The basic premise of the new proposal presented here is that the collider energy, even if constrained by the present tunnel radius, is a parameter which is more interesting than the luminosity. This argument has been heard before; one such in the case of ISABELLE versus the TEVATRON was that a factor of 2 in energy was comparable to an order of magnitude in luminosity. John Yoh has done some preliminary comparisons of proposed collider upgrades and heavy quark production and has come to even more surprising conclusions.[1]

Another equally important motivation for developing the concept of a higher energy Tevatron pbar-p Collider is the faith that Fermilab has the skill and motivation to do the job well. In particular, higher field replacements for present-day Tevatron magnets are natural endeavors for our magnet specialists. Also, the next few years of Tevatron operation will certainly lead to improvements and inventions which will increase the capabilities of the pbar source and the Collider itself.

Unlike improvements which primarily benefit the colliding beam operation, an energy increase is directly applicable to the fixed target operation of the machine. Perhaps the replaced Tevatron magnets will prove useful in the upgrade of the external target areas to 2 TeV. Finally, if the SSC were to be sited at Fermilab, the increased energy available for injection into the SSC could make life easier.

Basic Scheme

With very few changes, Fermilab is following the plan of the proposal discussed below. The major new aspect is an initiative to develop the highest field replacements possible for the Tevatron magnets. This would be in the spirit of improved superconducting technology that gave us the Tevatron in the first place. The goal of the project would be to have the new designs ready in three years, such that the replacements could be built and installed by 1994. Perhaps too large to be considered an Accelerator Improvement Project, the spirit of the proposal is meant to be an AIP request.

While it is true that an increased energy for the collider coupled with the two 20 GeV ring upgrade to the injector would make a superior plan, the spirit of this document is that resources are limited both in money and manpower. Our present 5 year plan for operation and improvement of the Tevatron could be jeopardized by large construction projects like a new Main Injector and pp Collider or even two new 20 GeV Rings. This may be even more likely considering the possible impact of the SSC on the Accelerator Division.

Magnet Development

The European proposal for the LHC is based on a high field dipole magnet design of 10 Tesla. While somewhat ambitious, the point is that some experts believe that such a field is possible. A program for developing high field magnets is underway at CERN and there is already an industry-produced prototype (1.5 m long with a 5 cm coil diameter) which has run at 9.1 T.

Two TeV in the Tevatron tunnel requires a dipole field of 8.8 T.

Luminosity Development

The discovery of rare processes is surely the goal of any collider improvement program. By increasing the energy of the Tevatron, the ability to discover rare processes is improved by the fact that both cross-sections and luminosity increase.

The "Proposal for a Dedicated Collider at the Fermi National Accelerator Laboratory" (May, 1983) contains many of the arguments for a collider at 4 TeV center of mass energy. While the theoretical prejudices may have changed a bit in the last 5 years, none of the particles to be discovered have yet been seen. The calculations in the proposal show typical increases of an order of magnitude in the production cross-sections for heavier hypothetical particles for a factor of two in energy. There is also some indication that some of the backgrounds for certain types of signatures for these particles rise less rapidly with energy. That is, the signal to noise ratio may be more favorable for a higher energy collider compared to a lower energy machine with much higher luminosity.

These factors are particularly important for detectors with luminosity limitations. While the SSC design studies have indicated that special detectors with limited goals can be designed to operate at L > 10^{33}, it may turn out that even very expensive upgrades of the CDF and BO detectors cannot allow practical luminosities as high as 10^{32}. Provided that the maximum attainable luminosity is matched to the detector capability, the only way to improve the discovery potential of the Tevatron is to increase its energy.

Luminosity increases with energy due to the adiabatic damping of the transverse beam sizes. This luminosity factor scales directly with energy; namely, if all the fields in the Tevatron are scaled by a factor of two then the luminosity also increases by a factor of two.

What is the maximum attainable pbar-p luminosity and corresponding integrated luminosity of a 2 TeV on 2 TeV machine operating in 1994?

Source

Many studies have shown that peak luminosities of more than 5 10^{31} $cm^{-2}s^{-1}$ at 1 TeV can be calculated for beam parameters which are not far from what we have in the present pbar-p collider. The schemes involve many bunches and the use of electrostatic separators to reduce the head-on beam-beam tune shift. There are two problems with these schemes which were solved on paper with the addition of the two 20 GeV Rings. The major problem was that the pbar accumulation rate is too low to compensate for the loss of particles just due to the total cross-section with two interaction regions operating at high luminosity. The other problem is that the accumulator cannot store enough pbars to do a complete fill of the Tevatron.

In fact, at a luminosity of 10^{32} the two interaction regions would use a total of 2 10^7 pbars/s assuming a total cross-section of 100 mb. This is a close match to the TeV I design accumulation rate of 2.5 10^7. Failure to reach this design rate and the large transfer inefficiencies, including large losses in the MR, have led to pessimism regarding the future of pbar-p colliders. Considering the conservative design of the source and how it might be improved as a matter of course, especially the use of the full potential of the MR to target protons and the possibility of increasing the stochastic cooling bandwidth, such pessimism is premature at best.

Even considering that the pbar production cross-section is 40% of what was expected, the MR presently has the capability to saturate the Source with antiprotons. Stochastic cooling rates are inversly proportional to the number of particles being cooled. As a consequence, a reduced production cross-section can be compensated by increasing the Debuncher cycling rate. The maximum rate is limited by the lithium lens and, eventually, by the mechanical motion of the Accumulator injection kicker shutters. Two pbar production target systems which operate on alternate batches of incident protons have been proposed as a way around the lithium lens problem. By 1994, one should expect the source to be operating well beyond the TeV I design accumulation rate, providing sufficient support exists for basic R & D.

A complete fill of the high luminosity Tevatron takes about $3\ 10^{12}$ pbars. The present source design is limited to less than 10^{12} and suffers a reduced stacking rate as this limit is approached. One possibility is a 20 GeV accumulator which has been discussed. Another possibility is to use the Tevatron itself as a storage device by replacing a fraction of the circulating pbars in the Collider as soon as the Accumulator is refilled. This involves decelerating the colliding beams in the Tevatron down to the injection energy, aborting the unwanted particles, reinjecting pbars and protons, and reaccelerating. While this scheme may sound complicated and difficult, it may not be. Machine study time could help resolve questions of this sort.

Another solution to the accumulator intensity limit may come from larger proton bunch intensities. The proton bunch intensity can probably be increased substantially beyond the $6\ 10^{10}$ per bunch assumed in the Tevatron I design. Bunches of $9\ 10^{10}$ were successfully injected into the Tevatron during the 87 collider run. Improvements to the bunch rotation system have been made since then, and the Linac upgrade may allow even higher proton intensities in the more distant future. It may be possible to produce high luminosity with more protons and fewer pbars per fill which would make the accumulator limit less of a problem. In this mode, the luminosity lifetime would suffer; for example, with 10^{12} pbars and a loss rate of $2\ 10^{10}$ pbars/s, refills would have to be made more often than every 10 hours.

Main Ring

The most appealing aspect of the plan to replace the MR with a Main Injector which is in a new tunnel is the reduction of interferences between the pbar production operation of the MR and the detector operation. Not only are accidental losses a problem to the experiments, but the MR operation has surely degraded because of the overpasses. The inefficiency in the transfer from the 8 GeV Accumulator to the 150 GeV has been a major problem for the pbar ecomomics for collider operation.

Unfortunately, these problems cannot wait to be solved. For the next 5 years these difficulties with the MR will be the focus of much of the accelerator development program. Time will tell if the only rational solution is a complete rebuild in another tunnel or the addition of another ring between the Booster and the MR.

Tevatron

By 1994 the Tevatron itself should be a mature device with stable operation and very long lifetimes. Multibunch operation with electrostatic separators will be well understood, with new techniques and inventions beyond those we are now contemplating.

The low beta insertions which will be in place at the time of the energy upgrade will be capable of a minimum beta of 25 cm at 1 TeV. A 40 cm solution at 2 TeV with the same devices should be possible. Since the bunch length is longer than either of these numbers, the luminosity will not be degraded very much because of the larger beta star. On the other hand, the effective interaction region would be longer with corresponding loss of detector efficiency. A search for a 25 cm beta at 2 TeV would be worth doing.

The strength of the electrostatic separators should also be increased for 2 TeV operation. To have a separation of the same number of beam widths as at 1 TeV, the line integral of the separator strengths should increase by 1.414. By the time of the energy upgrade we may know how to make higher voltage plates and/or we may be more comfortable with smaller separations between the p and pbar beams.

Detector Implications

With no improvement in the luminosity of the Tevatron beyond what is available by 1993, the two major detectors would get a renewed existence just from an increased center of mass energy. In fact, one expects that the detectors will already be coping with luminosities greater than 5 10^{30} by the time Tevatron magnet replacements are ready to be installed. Hopefully, the next order of magnitude luminosity capability upgrade will be planned to coincide with the installation period.

One major change to be contemplated at the time of the energy redoubler installation would be a new design of the MR overpass at the D0 detector. One possible improvement would be to put a new Main Injector in another tunnel. On the other hand, practical experience with the B0 overpass may lead to suggestions for a new overpass design for D0.

Costs

Manpower

The most immediate need is for a rejuvenated magnet development effort. Some idea of the costs of high field magnets will have to be developed by some real experts.

Improvements to the present pbar-p luminosity are the next most important developments to pursue. Higher frequency stochastic cooling devices and correspondingly shorter production cycle times with multibunch MR operation should be supported with enthusiasm and people. A vigorous program of machine studies related to electrostatic separators, multibunch operation, and operational modes like acceleration/deceleration cycles in the Tevatron are of great interest. Questions of the aperture needed for separated orbits need to be answered to provide feedback to the magnet upgrade effort.

Funds

In principle, all that is needed for the energy upgrade is new Tevatron magnets. We can assume for the sake of argument that all other major systems (refrigeration, spool pieces, controls, etc.) will be reused. Under these conditions, one can guess that the new magnets will be more expensive than the old ones since they go to higher field. The quench protection system will also be different and perhaps more costly. Additional refrigeration may be required, especially if the new magnets need to run at lower temperature.

If the present Tevatron magnets could be rebuilt today for $80M (my guess), the corresponding costs for high field versions might be near $200M. While this factor of 2.5 in cost is somewhat arbitrary on my part, it could be affected dramatically by a vigorous magnet development program.

Conclusions

The next 5 years of Tevatron operation have the potential to be the most exciting and rewarding period in Fermilab's history. We have a corner on the market, so to speak, which will allow us to do physics that no other machine can do.

A natural extension to the pbar-p collider program is an energy upgrade. With some optimism and a lot of hard work the luminosity to exploit the higher energy will be available by the time the energy can be increased.

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[1] John Yoh has compared the following four cases for a 10^7 s run to find the highest mass which could be discovered in the process hadron+hadron goes to t+tbar+anything, where 50 events are produced (leading to 7 observed events):

Beams	Energy	Luminosity	Discovery Limit
p + p	1 TeV	5 10^{32}	305 GeV
pbar + p	1	5 10^{31}	325
pbar + p	1.5	1 10^{31}	335
pbar + p	2	1 10^{31}	400